

UNITED STATES PATENT APPLICATION

FOR

**RUBIDIUM-82 GENERATOR BASED ON SODIUM NONATITANATE
SUPPORT, AND IMPROVED SEPARATION METHODS FOR THE RECOVERY
OF STRONTIUM-82 FROM IRRADIATED TARGETS**

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RUBIDIUM-82 GENERATOR BASED ON SODIUM NONATITANATE SUPPORT, AND IMPROVED SEPARATION METHODS FOR THE RECOVERY OF STRONTIUM-82 FROM IRRADIATED TARGETS

BACKGROUND OF THE INVENTION

Field of the Invention

This invention relates to the selective separation of strontium-82 from other radioisotopes, such as those resulting from an irradiated molybdenum target, and in the manufacture of a rubidium-82 generator.

Background of the Related Art

The use of radioisotopes as diagnostic and imaging agents in medicine has expanded rapidly in recent years. Positron (β^+) emitters are particularly useful in the study of metabolic processes because the positron-electron annihilation reaction produces a pair of gamma rays with an energy level of 511 keV travelling in opposite directions. By placing a series of detectors around a patient who has been administered a positron emitter, both the location and amount of radioactivity can be accurately determined. This property is utilized in Positron Emission Tomography (PET) to image metabolic processes *in vivo*. Rubidium-82 (^{82}Rb) is a short-lived positron-emitting isotope ($T_{1/2} = 75$ seconds) that is increasingly being used to study blood flow through the heart and brain. Physiologically, rubidium is an analogue of potassium, and consequently enters the body's large potassium pool, which has a comparatively slow turnover. Thus, after ^{82}Rb is injected intravenously, the tracer's uptake in tissue reflects the rate of delivery, i.e. blood flow, and thus ^{82}Rb rapidly builds up in the heart. This can be used, for example, to study blood-brain barrier leakage and heart muscle perfusion.

The short half-life of ^{82}Rb means that it must be supplied to physicians in the form of a generator, where the parent ^{82}Sr ($T_{1/2} = 25$ days) is immobilized on a solid substrate or support and ^{82}Rb eluted as required. The generators that are currently available use hydrous tin oxide to immobilize the ^{82}Sr and allow the elution of ^{82}Rb by saline or other appropriate eluant. The ^{82}Sr ($T_{1/2} = 25$ days) is accompanied by unwanted ^{85}Sr ($T_{1/2} = 64$ days), generated as a by-product during the manufacture of ^{82}Sr , wherein both isotopes have a relatively long half-life and a high radiotoxicity due to their tendency to accumulate in bone. Thus, it is essential to minimize or eliminate the introduction of ^{82}Sr and ^{85}Sr into a patient during the administration

of ^{82}Rb . Although hydrous tin oxide has proved acceptable to date for use in generators, new materials exhibiting far higher strontium affinities, improved strontium/rubidium separation factors and greater radiolytic stability are needed in order to lower the amount of ^{82}Sr and ^{85}Sr released during elution of the ^{82}Rb .

The parent ^{82}Sr is generated by the proton irradiation of rubidium, rubidium chloride or molybdenum targets followed by dissolution and processing to isolate the ^{82}Sr . The demand for ^{82}Rb generators has grown so great that there is a need to reduce processing times and to increase the yield of ^{82}Sr from processed targets. One method of improving the supply of ^{82}Sr is to improve the processes used to extract ^{82}Sr from irradiated targets. Current methods utilize organic ion exchange or chelating resins to extract very low levels of strontium from dissolved targets containing molar concentrations of inert ions. However, a satisfactory separation of ^{82}Sr from the target materials and other radioisotopes generated during the irradiation procedure requires multiple treatment steps due to the relatively low affinity and low selectivity of the organic ion exchange resins for ^{82}Sr .

^{82}Sr is produced by the proton irradiation of molybdenum metal, rubidium metal and rubidium chloride targets. The irradiation process also produces a range of other radioactive isotopes (e.g. ^{88}Y , ^{88}Zr , ^{85}Sr) and as a consequence, a series of carefully designed separation procedures have been designed to separate the desired ^{82}Sr from other radioisotopes and inactive species present. The primary method used to separate ^{82}Sr is by a series of ion exchange and selective elution steps. Typically, AG 50 W-X8 ion exchange resin is used to separate ^{82}Sr from dissolved targets. However, this resin is relatively non-selective and will absorb numerous polyvalent cations (e.g., ^{88}Y) in addition to the desired ^{82}Sr . Consequently, multiple separation steps are required to isolate ^{82}Sr from the other isotopes present.

^{82}Rb can be conveniently supplied to physicians in the form of a generator in which the parent ^{82}Sr is immobilized on an ion exchange material and the ^{82}Rb eluted when required. This means that ^{82}Rb PET can be performed at clinical facilities where a typical generator may last several months before the yield of ^{82}Rb diminishes below a usable level.

To be suitable for use in a ^{82}Rb generator, an ion exchange material must exhibit a high affinity for strontium but a low affinity for rubidium, allowing the ^{82}Rb daughter to be eluted from a column containing immobilized ^{82}Sr . Generators have been proposed that were based on a number of separation media including Chelex 100, Al_2O_3 , Sb(V) hexacyanoferrate, polyantimonic acid, titanium vanadate and hydrated tin(IV) oxide, with the hydrated tin(IV) oxide being the most widely used.

However, the crucial component of any system is the actual ion exchange material containing the immobilized ^{82}Sr parent. Current systems using hydrous tin oxide have a limited life due to the breakdown of the hydrous tin dioxide, necessitating frequent replacement.

Therefore, there is a need for a highly strontium selective ion exchange material in place of ion exchange resins and hydrated tin(IV) oxide, so that the separation and recovery of ^{82}Sr from Rb, RbCl and Mo targets is greatly facilitated. This will lead to a reduction in processing steps, a decrease in target processing times and thus a decrease in the cost of the ^{82}Sr product. There is also a need for an ion exchange material suitable for use as a ^{82}Rb generator having a very high selectivity for ^{82}Sr and a very low selectivity for ^{82}Rb to allow elution of the ^{82}Rb by isotonic saline or other solutions.

SUMMARY OF THE INVENTION

The present invention provides a method of chemically isolating strontium-82 from proton-irradiated molybdenum targets. This comprises dissolving the molybdenum metal target containing the strontium-82, adjusting the pH of the dissolved molybdenum target solution to an alkaline pH, removing precipitates from the solution, and then absorbing the strontium-82 from the solution onto a support comprising sodium nonatitanate. Sodium nonatitanate can also be applied to the efficient recovery of strontium-82 from alkaline RbCl solutions produced during the processing of proton-irradiated rubidium metal and rubidium chloride targets.

The present invention also provides a rubidium-82 generator, comprising a strontium-82 support medium comprising sodium nonatitanate. Preferably, the sodium nonatitanate is characterized by a strontium selectivity greater than 250,000 mL/g at an alkaline pH, and/or the sodium nonatitanate is characterized by a rubidium selectivity less than 100 mL/g at an alkaline pH. More preferably, the sodium nonatitanate is characterized by a strontium/rubidium separation factor greater than 1,000, and even more preferably greater than 100,000.

The rubidium-82 generator is prepared by a process comprising: preparing sodium nonatitanate from titanium isopropoxide and aqueous sodium hydroxide; heating the sodium nonatitanate at a temperature between 100°C and 250°C for a period between 12 hours and 2 weeks; and absorbing strontium-82 on the sodium nonatitanate from an aqueous solution comprising strontium-82 and a soluble sodium salt, wherein the sodium salt concentration is between 0.1 and 1 molar. It is also preferred that the titanium isopropoxide and the aqueous

sodium hydroxide solution are provided at a sodium hydroxide to titanium isopropoxide molar ratio of greater than 0.44, but preferably providing a large molar excess of sodium hydroxide. The sodium hydroxide to titanium isopropoxide molar ratio is preferably between 1 and 10, more preferably between 2 and 6, and most preferably about 4.

Furthermore, the invention provides a process for preparing a solution containing rubidium-82. The process comprises providing a solution containing strontium-82 at a pH between 10 and 14, absorbing the strontium-82 from the solution onto a sodium nonatitanate support medium, and eluting rubidium-82 from the sodium nonatitanate support medium with a solvent. The solvent is preferably selected from the group consisting of water and saline solutions. More particularly, the solvent may be an aqueous solution having a sodium chloride concentration between 0.001 molar and 1 molar, preferably between 0.2 molar and 1 molar. The solvent may also be a pharmaceutical grade isotonic saline and buffer solution.

DETAILED DESCRIPTION OF THE INVENTION

The present invention provides improved sodium nonatitanate compositions, a method using the composition for recovery of ^{82}Sr from irradiated targets, and a method using the composition for generating ^{82}Rb . The sodium nonatitanate materials of the invention are far more selective at separating strontium from solutions derived from the dissolution of irradiated target materials than current ion exchange resins used in the production of ^{82}Sr . The present invention reduces the number of processing steps required, and thus leads to a decrease in target processing times and a reduction in the cost of the ^{82}Sr product. Waste generation and disposal are also decreased.

According to the present invention, synthetic conditions are adjusted to produce a material with improved properties more applicable to ^{82}Sr processing. The sodium nonatitanate of the present invention has been found to have a very low affinity for rubidium in addition to an exceptionally high affinity for strontium, making it ideal for use as a replacement for the hydrous tin dioxide used in current ^{82}Rb generators. Sodium nonatitanate materials of this type will both improve the recovery of ^{82}Sr and lead to a safer, more effective ^{82}Rb generator system for clinical applications.

Sodium nonatitanate, $\text{Na}_4\text{Ti}_9\text{O}_{20} \cdot x\text{H}_2\text{O}$, is an inorganic ion exchange material that has been used for the removal of ^{90}Sr from neutral and alkaline nuclear wastes. The sodium nonatitanate of the present invention has a number of advantages over conventional organic ion exchange resins (e.g., Chelex 100) that include: very high selectivity for trace levels of strontium

in the presence of molar concentrations of other ions at alkaline pH; very low affinity for rubidium; excellent radiation, chemical and thermal stability so that there is no release of contaminants (e.g. Ti) into the ^{82}Rb product; rapid reaction kinetics; high cation exchange capacity; absorbed ions readily stripped by treatment with dilute mineral acid allowing the sodium nonatitanate to be recycled, if desired; scale up of similar synthesis has already been demonstrated; and the sodium nonatitanate powder can be manufactured into pellets appropriate for column operations. Other chemically related sodium titanate materials suitable for use in the same manner as the aforementioned sodium nonatitanate ($\text{Na}_4\text{Ti}_9\text{O}_{20} \cdot x\text{H}_2\text{O}$) include other titanate materials exhibiting high Sr affinity and low Rb affinity, including Sr-Treat (available from Selion Oy) and monosodium titanate (available from Boulder Scientific). It is also anticipated that analogous zirconates may exhibit similar properties.

The invention also provides important improvements in the processing of irradiated targets to recover ^{82}Sr . Sodium nonatitanate has a much greater affinity for ^{82}Sr than currently used ion exchange resins, and a low affinity for other radioactive isotopes. Consequently, the use of sodium nonatitanate greatly simplifies the extraction process by reducing the number of separation steps that are required to produce chemically pure ^{82}Sr . Thus, targets can be processed more rapidly and the recovery of ^{82}Sr improved. Improved isotope selectivity may also facilitate the isolation of other useful isotopes from the targets, leading to greater payback from target processing operations.

Furthermore, less than 1g of sodium nonatitanate material is needed in a ^{82}Rb generator and 1 kg of this material is expected to be sufficient to process a large number of targets, even if the sodium nonatitanate material is not recycled and is disposed of after one use. Consequently, the additional cost incurred by the use of sodium nonatitanate will be negligible in comparison with the cost savings achieved in the ^{82}Sr production.

It has been determined that replacing hydrous tin dioxide with sodium nonatitanate reduces the amount of ^{82}Sr released during the operation of the ^{82}Rb generator, thereby reducing the exposure of the patient to ^{82}Sr . Sodium nonatitanate is also more chemically stable and less likely to leach non-radioactive contaminants into solution during operation of the generator. The sodium nonatitanate is also more amenable to recycling since the ^{82}Sr can readily be stripped with mineral acid without producing additional impurities. Recycling of ^{82}Sr generators is already being used as a source of additional ^{82}Sr , and improvements to the recycling procedure (obtained by using a superior ion exchange material) will facilitate the recovery of ^{82}Sr from this source.

Although the sodium nonatitanate may be used as a direct replacement for hydrous tin dioxide in the ^{82}Rb generator, it is also possible to use sodium nonatitanate in the form of a disposable add-on filter that could be used to trap any ^{82}Sr that is leached from the generator during the production of ^{82}Rb .

The first step in preparing a ^{82}Rb generator is to load the parent ^{82}Sr onto the sodium nonatitanate material and place the ion exchange material into a suitable column. It is essential that sufficient time be allowed for the ^{82}Sr to be absorbed by the sodium nonatitanate material in order to maximize the loading of the parent radioisotope per gram of ion exchange material.

Sodium nonatitanate should be loaded with ^{82}Sr before being placed in an ion exchange column, to avoid preferential loading of the ^{82}Sr on the top of the ion exchange column rather than uniformly throughout the material. This high concentration of radioactivity on a very small volume may result in undesirable radiolytic problems. Although sodium nonatitanate has been shown to be highly resistant to radiation damage, it is considered prudent to avoid any potential problems.

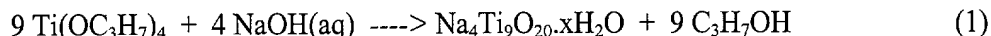
EXAMPLES

These Examples investigated the suitability of sodium nonatitanate for the use in separating ^{82}Sr from irradiated targets and in the construction of a $^{82}\text{Sr}/^{82}\text{Rb}$ generator. Initial batch experiments compared the rubidium and strontium selectivities of a number of different sodium nonatitanate samples with commercially available ion exchange materials (e.g. AW 500, Chelex 100) and some experimental materials that had also exhibited high strontium selectivities (e.g. sodium titanate). Column experiments were then performed using target simulants and generator simulants on materials that exhibited favorable selectivity characteristics. Some work was also performed to investigate the likely interference from other isotopes present in irradiated targets on the production of ^{82}Sr .

Example 1 - Preparation of Sodium Nonatitanate

Sodium nonatitanate (NaTi) was synthesized hydrothermally as follows. 77.5 g of titanium isopropoxide was added to 84.35 g of a 50 wt.% solution of NaOH with vigorous stirring and 60 mL of deionized water was added. The resultant gel was heated at approximately 108°C for 3 hours, transferred to a hydrothermal pressure vessel with an additional 90 mL of deionized water, and heated at either 170°C or 200°C for times ranging from 21 hours to 1 week. After the allotted time, the materials were filtered, washed with ethanol to remove residual base

and dried at 60°C. The mass of sodium nonatitanate produced was approximately 31 g. Each sample was characterized using x-ray powder diffraction (XRD). The reaction is outlined in Equation 1.



The crystallinity of the material was shown to be dependent upon the reaction time and temperature, with the most crystalline materials being produced after 1 week of hydrothermal treatment (200°C for 7 days). Samples that received no hydrothermal treatment, or only a few days, were virtually amorphous with only a few very broad reflections visible on the XRD pattern.

The theoretical cation exchange capacity (CEC) of sodium nonatitanate is quite high and has a value of 4.74 meq/g, which compares favorably with organic ion exchange resins.

Alternative titanium salts that could be used to manufacture sodium nonatitanate include titanium tetrachloride, TiCl_4 , and titanium sulfate, $\text{TiOSO}_4 \cdot x\text{H}_2\text{SO}_4 \cdot y\text{H}_2\text{O}$. However, hydrolysis of these salts leads to the generation of hydrochloric acid and sulfuric acid, respectively, and thus additional base is required during the hydrothermal process. The final product also needed to be exhaustively washed to remove residual sodium chloride or sodium sulfate. Consequently, titanium isopropoxide (which hydrolyzes to form propanol) is the preferred starting material because the final product is free from additional sodium salts.

Example 2 - Determination of Strontium Selectivity

Sodium nonatitanate and a variety of other ion exchange materials were obtained and evaluated for use in the separation of ^{82}Sr from targets and in a ^{82}Rb generator. These materials are described below in Table 1.

Table 1. Characteristics of ion exchange materials evaluated in this study.

Material	Source	Sample Preparation
Na-Clinoptilolite	GSA Resources, AZ	Ground to powder.
AW500	Aldrich (1.6 mm Pellets)	Ground to powder.
Hydrous SnO_2	Synthesized in house	$\text{NaOH} + \text{SnCl}_4$. Washed with acetic acid/sodium acetate buffer.
K+ Pharmacosiderite ($\text{K}_3\text{H}(\text{TiO})_4(\text{SiO}_4)_3 \cdot 4\text{H}_2\text{O}$)	Synthesized according to literature method.	None. Used as synthesized.

Sodium Titanosilicate (Na ₂ Ti ₂ O ₃ SiO ₄ ·2H ₂ O)	Synthesized according to literature method.	None. Used as synthesized.
AG 50W-X8 (Na+) (25 - 50 Mesh)	BioRad. Strong acid ion exchange resin.	Converted to Na+ form (for alkaline solutions only)
Chelex 100 (Na+) (50 - 100 Mesh)	BioRad. Chelating resin with iminodiacetic acid functionality.	None. Used as received.
Sodium Nonatitanate	Honeywell, IL	None. Used as received.
Hydrous SiO ₂	Synthesized in house	Acetic acid hydrolysis of tetraethyl orthosilicate. Washed with H ₂ O
Hydrous TiO ₂	Synthesized in house	Hydrolysis of titanium isopropoxide. Washed with H ₂ O
Hydrous ZrO ₂	Synthesized in house	ZrOCl ₂ + NaOH. Washed with deionized water.

The strontium selectivity of the ion exchange materials of Table 1 was evaluated in sodium chloride and rubidium chloride solutions using radiotracer techniques. Samples were evaluated using a simple batch technique to allow the rapid screening of a large number of materials over a range of ionic strengths. Blanks were run for each matrix to check for any loss of strontium during filtration or absorption of strontium onto the scintillation vials. In all solutions evaluated, strontium absorption was negligible.

0.05g of each of the ion exchange materials was contacted with 10 mL of a solution, spiked with ⁸⁹Sr, in a capped scintillation vial. (The total strontium content was approximately 1.6 ppm, thus preventing any loss of strontium in solution due to precipitation of sparingly soluble Sr(OH)₂ at alkaline pH values.) The mixtures were shaken for 6 hours, filtered through a 0.2 μm syringe filter and the residual activity determined using liquid scintillation counting (LSC). Distribution Coefficients (K_d values) were then determined according to Equation 2:

$$K_d = (A_i - A_f) / A_f * v/m \quad (2)$$

where: A_i = initial activity in solution (counts per minute (cpm)/mL)

A_f = final activity in solution (cpm/mL)

v = volume of solution (mL)

m = mass of exchanger (g)

The final pH of the solution was also noted. The period of 6 hours was chosen to allow equilibrium to be reached for each of the ion exchange materials. However, previous work on the titanosilicates and titanates had shown the reaction rates to be rapid with the majority of the uptake occurring in only a few minutes. The concentration of the chloride solutions was varied from 1M to 0.001M to evaluate the effect of increasing Rb⁺ and Na⁺ concentrations on the uptake of Sr²⁺. All experiments were performed in duplicate, and if significant variations between duplicate samples occurred, the experiments were repeated until good agreements on the K_d values were obtained. The results are shown in Tables 2 and 3 and represented the average K_d obtained, quoted to 3 significant figures.

Table 2. Strontium selectivity data from unbuffered sodium chloride solutions.

Ion Exchange Material	K _d mL/g			
	1M NaCl	0.1M NaCl	0.01M NaCl	0.001M NaCl
Na-Clinoptilolite	8	124	3,260	36,900
AW500	1,860	88,300	1,270,000	1,210,000
Hydrous SnO ₂	767	43,000	124,000	51,800
K ⁺ Pharmacosiderite	18,300	251,000	594,000	281,000
Sodium Titanosilicate	556,000	273,000	119,000	42,900
AG 50W (Na ⁺)	32	3,380	365,000	2,510,000
Chelex 100 (Na ⁺)	610	26,400	726,000	1,300,000
NaTi (Honeywell)	80,600	1,030,000	258,000	166,000
NaTi (No hydrothermal)	1,530,000	2,570,000	739,000	372,000
NaTi (170°C, 21hr)	1,030,000	1,240,000	272,000	172,000
NaTi (170°C, 3d)	959,000	633,000	218,000	93,100
NaTi (170°C, 7d)	167,000	834,000	264,000	90,400
NaTi (200°C, 21hr)	439,000	1,390,000	197,000	120,000
NaTi (200°C, 3 d)	261,000	898,000	251,000	158,000
NaTi (200°C, 7d)	195,000	955,000	265,000	214,000
ZrO ₂	3,360	52,200	213,000	232,000

Table 3. Strontium selectivity data from unbuffered rubidium chloride solutions

Material	K _d mL/g			
	1M RbCl	0.1M RbCl	0.01M RbCl	0.001M RbCl
Na-Clinoptilolite	19	3	88	11,000
AW500	9,750	107,000	1,020,000	1,280,000
Hydrous SnO ₂	766	66,100	104,000	51,800
K ⁺ Pharmacosiderite	1,950	40,800	419,000	427,000
Sodium Titanosilicate	12,600	94,700	164,000	179,000
AG-50W (Na ⁺)	44	3,870	237,000	800,000
Chelex 100 (Na ⁺)	1,580	38,400	555,000	977,000
NaTi (Honeywell)	13,900	108,000	279,000	324,000
NaTi (No hydrothermal)	14,220	116,000	345,000	429,000

NaTi (170°C, 21hr)	10,500	71,700	193,000	205,000
NaTi (170°C, 3d)	15,100	39,500	68,000	95,200
NaTi (170°C, 7d)	23,000	55,800	31,200	110,000
NaTi (200°C, 21hr)	11,000	66,400	110,000	103,000
NaTi (200°C, 3 d)	10,600	56,800	146,000	158,000
NaTi (200°C, 7d)	10,500	57,400	146,000	158,000
ZrO ₂	3,000	42,400	184,000	221,000

Comparing the selectivity data from sodium and rubidium solutions, it is evident that rubidium ions cause a reduction in affinity for the strontium ion for all of the exchangers indicating that the affinity of these materials for rubidium is significantly higher than the affinity for sodium ions. The pH of the final solutions was generally alkaline for the nonatitanates (NaTi) and titanosilicates, with pH values as high as 12 being measured. This was due to hydrolysis of the exchangers resulting in the absorption of protons and the release of sodium ions, thus increasing the pH of the aqueous phase. This effect can be overcome, if desired, by buffering the solution.

The most distinct trend was observed in 1M NaCl solutions for the sodium nonatitanate samples. The highest K_d was observed for the non-hydrothermal material and the K_d values decreased with increasing reaction time for both the 200°C and 170°C materials. Clearly, strontium uptake is facilitated by having a low-crystallinity material. This suggests that as the crystallinity increases and the size of the nonatitanate crystallites also increases, it becomes thermodynamically less favorable for exchange of the sodium ions by strontium. It is also interesting to note that the majority of the sodium nonatitanates exhibit a higher selectivity for strontium in 1M NaCl than in 0.001M NaCl. This indicates that the higher ionic strength facilitates the $\text{Na}^+/\text{Sr}^{2+}$ exchange reaction and more than compensates for the increased competition for the ion exchange sites from the additional Na^+ ions.

This data shows that sodium nonatitanate is an ideal material for the recovery of ⁸²Sr from irradiated rubidium and rubidium chloride targets and in the manufacture of a ⁸²Rb generator.

Example 3 - Rubidium Selectivity from NaCl Solutions

For an ion exchange material to be suitable for use in a ⁸²Rb generator, it must have a very high selectivity for strontium to prevent any loss of ⁸²Sr from the ion exchange column and release to the patient undergoing a PET scan. This property was clearly demonstrated in Example 2. It must also have a very low selectivity towards rubidium, thus allowing ⁸²Rb to be released

into solution as saline is passed through the ^{82}Rb generator. Consequently, the rubidium selectivity of the ion exchange materials was evaluated in sodium chloride media following the procedure described in Example 2. The same procedure was followed using ^{86}Rb to spike the solutions to give an activity of approximately 200,000 cpm/mL. Total rubidium in solution was < 0.05 ppm. The selectivities of the materials are shown below in Table 4.

Table 4. Rubidium selectivity data from unbuffered sodium chloride solutions.

Material	86Rb K_d mL/g			
	1M NaCl	0.1M NaCl	0.01M NaCl	0.001M NaCl
AW500	116	620	4,920	21,900
Hydrous SnO_2	1	6	36	290
K+ Pharmacosiderite	148	475	2,030	4,020
Sodium Titanosilicate	8,010	194,000	114,000	75,800
AG 50W (Na+)	7	75	688	6,680
Chelex 100 (Na+)	3	8	43	256
NaTi (Honeywell)	9	102	488	817
NaTi (No hydrothermal)	4	59	280	446
NaTi (170°C, 21hr)	9	56	209	297
NaTi (170°C, 3d)	7	46	198	311
NaTi (170°C, 7d)	3	15	47	71
NaTi (200°C, 21hr)	8	79	334	502
NaTi (200°C, 3d)	8	52	207	307
NaTi (200°C, 7d)	4	25	111	178
ZrO ₂	1	12	60	154

From the data in Table 4, it is clear that all of the sodium nonatitanate materials have a very low affinity for rubidium, particularly in the presence of relatively high amounts of sodium ions. In general, the rubidium selectivity decreased with increasing reaction time for both series of nonatitanates (170°C and 200°C) with the lowest affinity being demonstrated by the sample that was heated hydrothermally at 170°C for 1 week. Uptake was negligible in 1M NaCl and the very low reduction in activity that was noted could be accounted for by absorption of rubidium during filtration and by pipetting errors during the counting procedure. Consequently, samples with K_d values that were below 10 mL/g can be considered to have no affinity at all for ^{86}Rb . Some rubidium uptake was evident in very dilute sodium solutions, but the K_d values were low for all of the titanate samples. This suggests that the uptake of rubidium was more likely due to the materials having an exceptionally low affinity for sodium rather than any real affinity for rubidium. All of the sodium nonatitanate materials performed better than the commercially available sample obtained from Honeywell Inc. The materials are clearly ideal for use in a $^{82}\text{-Rb}$ generator.

Hydrous tin dioxide exhibited some of the lowest rubidium affinities and was comparable with Chelex 100, the best of the nonatitanates and the hydrous zirconium dioxide. However, hydrous tin dioxide exhibited much lower strontium K_d values than the nonatitanates. Therefore, nonatitanate materials are preferred because they have higher strontium/rubidium separation factors. Hydrous tin dioxide also has a limited pH stability range and significant dissolution and release of absorbed strontium is likely to occur should any significant pH perturbations occur outside the range of pH 4 to pH 9. Radiation stability of hydrous tin dioxide is also limited, with particle breakdown causing current 82-Rb generators to be replaced before decay has reduced the 82-Rb below useable levels.

The rubidium selectivity data also indicates that AW500, potassium Pharmacosiderite and the sodium titanasilicate have a strong affinity for rubidium in a range of saline solutions. Consequently, these materials will be unsuitable for use in a 82Rb generator and have only limited applications in the processing of irradiated target materials.

Example 4 - Sr and Rb Selectivity in 0.1M Sodium Acetate/Acetic Acid Buffer

In order to prevent hydrolysis reactions from raising the pH as described above, some strontium and rubidium selectivity experiments were performed in a 0.1M sodium acetate / acetic acid buffer solution. In these tests, the final pH remained between 5.2 and 6.3, which is a more clinically acceptable pH for an 82Rb infusion. Rubidium K_d values remained low, as expected, following the trend observed in Table 5. Strontium K_d values were considerably lower, with a maximum K_d value of 80,000 mL/g being obtained for the sodium nonatitanate sample that was heated hydrothermally at 170°C for 21 hours. This is considerably lower than the K_d value of over 1,200,00 mL/g that was obtained in unbuffered 0.1M NaCl. The K_d values obtained for the other ion exchange materials were also considerably lower. However, the Sr/Rb separation factors remained high and the sodium nonatitanates still outperformed hydrous tin dioxide and the organic ion exchange resins. The affinity of sodium nonatitanate for strontium is greatest at higher pH values.

Example 5 - Molybdenum Targets

The basic steps of a proposed process to obtain 82Sr from irradiated molybdenum targets are as follows:

1. Dissolve the irradiated molybdenum target in 30% hydrogen peroxide, ensuring excess hydrogen peroxide is destroyed.
2. Add sodium hydroxide to bring the pH to approximately 12.
3. Filter the solution to remove any precipitate. It is predicted that the majority of ^{88}Zr and ^{59}Fe will be found in the precipitate, and experiments already performed have confirmed that 99% or more of the ^{88}Y precipitated out of solution on the addition of NaOH .
4. Pass the solution through a column of sodium nonatitanate and wash the column with two bed volumes of 0.1M NaCl , adjusted to pH 12 with NaOH . ^{82}Sr and ^{85}Sr will be absorbed. ^{82}Rb and other Rb isotopes will remain in the aqueous phase. Molybdate anions will also pass through the column.
5. The column can then be stripped using dilute mineral acid to recover the ^{82}Sr and the sodium nonatitanate reused or discarded.

There is a range of other isotopes present in addition to ^{82}Sr , including ^{75}Se , ^{73}As , ^{74}As , ^7Be , ^{68}Ge , ^{48}V , ^{60}Co (and other Co isotopes), ^{54}Mn , ^{51}Cr and ^{95}mTc . In the alkaline target solution, Se, As, V, Ge, Cr, Mn and Tc are expected to be present as anions and thus will not be absorbed onto the sodium nonatitanate. Significant amounts of Co would be expected to precipitate when the target solution is neutralized, and thus little is expected to be available under alkaline conditions to absorb onto the sodium nonatitanate. The most likely isotope to be absorbed is beryllium, because it is a Group II metal with a similar aqueous chemistry to strontium. However, the affinity of sodium nonatitanate for Group II metals decreases in the order $\text{Sr} > \text{Ca} > \text{Mg}$. No data is available for beryllium, but if the trend continues, the affinity would be expected to be low. Thus, any absorbed ^7Be would be readily removed by an alkaline sodium chloride (or similar) wash.

The current process for recovering ^{82}Sr from irradiated rubidium metal and rubidium chloride targets requires minimal modification to facilitate the use of sodium nonatitanate. Both targets are processed following standard processing procedures to generate rubidium chloride solutions in an ammonia/ammonium chloride buffer solution. These solutions are then passed through a sodium nonatitanate column and washed with additional buffer to remove any weakly held rubidium cations. Strontium and possibly some other cationic species present will be absorbed onto the nonatitanate column, whereas rubidium cations, ammonium cations and anions will rapidly pass through the column. If additional cations are absorbed onto the sodium nonatitanate, they can be selectively removed by washing with an appropriate eluant (e.g. citrate,

nitrilotriacetate.) The strontium selectivity of sodium nonatitanate has been shown to be unaffected by a number of common complexants and as a consequence, it should be a relatively simple manner to elute any undesirable cations from the column, leaving pure 82/85Sr.

Figure 1 clearly shows the exceptionally high affinity of the sodium nonatitanate materials in comparison with the currently utilized organic resin Chelex 100. All of the sodium nonatitanates performed equally well in the buffered rubidium target solutions indicating that the synthetic conditions are not too important when the material is being used in solutions containing high concentrations of rubidium ions. Thus, by replacing the Chelex 100 with sodium nonatitanate, a more efficient 82Sr isolation can be achieved.

It has also been shown that it is possible to tailor the selectivity of the sodium nonatitanate to achieve the optimum Sr/Rb separation by manipulating the reaction conditions. The differing selectivities were most obvious in sodium solutions, with the less crystalline materials exhibiting the highest strontium distribution coefficients. However, the series of nonatitanates showed little difference in behavior when the predominant cation in solution was Rb+. The materials synthesized clearly demonstrated superior characteristics to the commercially available sample in almost all matrices evaluated. The majority of the sodium nonatitanate samples also exhibited greater strontium selectivities than hydrous tin dioxide in a range of sodium chloride solutions, from 1M to 0.001M. Rubidium selectivities were low, making the sodium nonatitanate ideal as a replacement for hydrous tin dioxide in a 82Rb generator.

Commercially, one method of 82-Sr production is via the proton spallation reaction with natural molybdenum metal targets. A simulated molybdate target solution was prepared as follows. 12.5 g of molybdenum powder was carefully dissolved in 30% H₂O₂ solution and made up to a total volume of 500 mL to produce a clear yellow solution of molybdic acid, H₂MoO₄. Solid sodium hydroxide granules totaling 10.9 g were then carefully added to neutralize the solution and bring the pH to approximately 12.3. The colorless solution was then filtered to remove any precipitate. This alkaline molybdate solution was spiked with either 86Rb or 89Sr and K_d values determined as described previously. Separation factors for the strontium/rubidium selectivity were also calculated by dividing the strontium K_d by the rubidium K_d, thus allowing the relative affinities of the ion exchange materials to be directly compared. The results are illustrated below in Table 5.

Table 5. Strontium and rubidium absorption from simulated molybdate target solutions

Material	Sr K _d mL/g	Rb K _d mL/g	Separation Factor
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AW500	7,070	194	36.4
K+ Pharmacosiderite	187,000	142	1320
Sodium Titanosilicate	547,000	6500	84.2
Chelex 100 (Na+)	3,120	5	624
AG 50W-X8 (Na+)	69	18	3.83
NaTi (Honeywell)	337,000	27	12,500
NaTi (No hydrothermal)	1,690,000	12	141,000
NaTi (170°C, 21hr)	1,000,000	12	83,300
NaTi (170°C, 3d)	829,000	14	59,200
NaTi (170°C, 7d)	324,000	3	108,000
NaTi (200°C, 21hr)	954,000	12	79,500
NaTi (200°C, 3 d)	687,000	11	62,500
NaTi (200°C, 7d)	772,000	9	85,800
ZrO ₂	168,000	8	21,000

From this data, it is clear that the sodium nonatitanate materials are far superior to Chelex 100 and AG 50W-X8 ion exchange resins for the recovery of ⁸²Sr from irradiated molybdenum targets. High K_d values in excess of 500,000 mL/g indicate that almost 100% strontium removal was achieved by some of the nonatitanate samples, with the residual strontium in solution approaching background levels. In the alkaline conditions used in this test, the Chelex 100 resin had the lowest affinity for strontium of all of the materials evaluated. The selectivity of the sodium nonatitanate for rubidium was lowest for the sodium nonatitanate material that was prepared by heating for 1 week at 170°C to obtain a relatively crystalline product. However, strontium selectivity also decreased with increasing reaction time.

The best overall strontium/rubidium separation factor was obtained for the material that had not undergone any hydrothermal treatment. All of the materials performed better than the commercially available nonatitanate materials. Thus, it is possible to alter the selectivity of the material by controlling the reaction conditions to produce an improved sodium nonatitanate material for use in ⁸²Sr separations. Rubidium selectivities were very low for all of the nonatitanates, indicating minimal rubidium absorption would occur in a column process and that any rubidium absorbed would be readily removed by a dilute saline wash.

The sodium titanosilicate, potassium Pharmacosiderite and AW500 exhibit selectivities for rubidium that are too high to allow their use in the selective removal of ⁸²Sr from irradiated molybdenum targets. This high selectivity would result in some rubidium being retained on the column that would not be readily removed by a simple saline wash, thus leading to contamination of the ⁸²Sr product with both radioactive and stable rubidium isotopes. Hydrrous tin oxide was not evaluated because, due to the amphoteric nature of tin, significant dissolution would be expected at a pH in excess of 12.

Example 6 - Acid Molybdate Target Solutions

Sodium nonatitanate has a relatively low affinity for strontium at pH values less than 6, and was not expected to exhibit any affinity for strontium from the acidic molybdate target solutions prior to the addition of sodium hydroxide. K_d values were determined to confirm this and to compare it with the K_d values for both Chelex 100 and AG 50W-X8 under identical conditions. The data obtained is shown below in Table 6.

Table 6. The affinity of selected ion exchange materials for strontium in acidic molybdate target solutions

Ion Exchange Material	Sr K_d mL/g	Final pH of Solution
Chelex 100	25	1.43
AG 50W-X8	18,300	1.42
Sodium Nonatitanate (Honeywell)	1,260	1.53

These data clearly indicate that for the processing of acid molybdate solutions, the strong acid ion exchange resin AG 50W-X8 is the preferred medium. However, the Sr K_d value of 18,300 mL/g in the acidic media is nearly two orders of magnitude lower than the K_d value of 1,690,000 mL/g that was obtained for the best of the sodium nonatitanate materials in alkaline molybdate solutions. Consequently, it is evident that ^{82}Sr can be recovered more effectively from alkaline solution using sodium nonatitanate than is currently achieved using AG 50W-X8 from acidic media.

Example 7 - Rubidium and Rubidium Chloride Target Solutions

The processing of either rubidium chloride or rubidium metal targets follows a similar procedure once the target has been successfully dissolved. In essence, ^{82}Sr needs to be selectively extracted from a solution of RbCl in a 0.1 M NH_3 / 0.1M NH_4Cl buffer adjusted to a pH of between 9 and 10. Batch experiments were performed in simulated buffer solutions to determine the strontium selectivity in the presence of high concentrations of rubidium ions. Only the ion exchange materials that exhibited high strontium selectivities in the initial scoping studies with NaCl solutions were evaluated. K_d values were obtained as described previously. Two rubidium chloride solutions were selected which represent typical rubidium concentrations obtained during the processing of rubidium metal (1.95 M Rb^+) and rubidium chloride targets (0.68 M Rb^+). In both cases, Chelex 100 is used in the preliminary step to remove the ^{82}Sr from

the buffered rubidium solutions. The K_d values for the ion exchange materials are shown in Figure 1.

In the buffered rubidium solutions, there is little difference between the different nonatitanates evaluated. This is in stark contrast to the sodium molybdate solutions where a large variation in the performance of the titanates was observed. The nonatitanates were clearly the most effective materials at removing strontium from the buffered solutions with strontium K_d values of around 15,000 mL/g in 0.68 M Rb⁺ solutions and approximately 5,000 mL/g in 1.96 M Rb⁺ solutions. By contrast, Chelex 100 ion exchange resin gave K_d values of less than 1,000 mL/g in both solutions. Hydrous titanium oxide and hydrous tin oxide also exhibited appreciable K_d values, but they performed less efficiently than the nonatitanates in both solutions. Consequently, this data demonstrates that using sodium nonatitanate in place of Chelex 100 ion exchange resin will greatly increase the amount of strontium extracted from the target solutions.

The ion exchange materials were also evaluated for their rubidium selectivity from 0.1 M NH₃ / 0.1M NH₄Cl buffer solution. The buffer was prepared, spiked with ⁸⁶Rb and the pH adjusted to approximately 9.25 with concentrated ammonia. ⁸⁶Rb K_d values were then determined following the method described earlier. All of the sodium nonatitanates had a K_d < 20 mL/g. The very low rubidium selectivity in the pure buffer is almost certainly due to competition from NH₄⁺ ions for the available ion exchange sites. Consequently, absorption of rubidium during the processing of rubidium and rubidium chloride targets will be minimal, and any rubidium absorbed will be readily removed by washing with additional 0.1 M NH₃ / 0.1M NH₄Cl buffer solution. Thus, a clean separation of ⁸²Sr from these targets can be obtained using sodium nonatitanate.

The performance could also be improved by removing the buffer and increasing the pH to improve the amounts of strontium absorbed. (Buffers were initially utilized to maximize the performance of the organic ion exchange resins currently used and are not essential to the ⁸²Sr recovery process.)

Example 9 - Kinetic Experiments

In order for the sodium nonatitanate materials to find applications in the processing of irradiated target solutions, they must exhibit fast ion exchange kinetics allowing solutions to be passed through an ion exchange column at an acceptable rate. The kinetics of strontium absorption from alkaline molybdate target solutions was evaluated using a simple batch procedure. Ion exchange material, in the amount of 0.05 g, was shaken with 10 mL of molybdate

solution spiked with ^{89}Sr to give a total activity of approximately 155,000 cpm/mL. After an allotted time, the material was filtered through a 0.2 m syringe filter and the activity in the aqueous phase determined by LSC. The results are shown below in Figure 2.

From the data in Figure 2, it is clear that the reaction kinetics for the sodium nonatitanate powder is extremely rapid, with over 99 % of the ^{89}Sr removed in only 1 minute. By contrast, the reaction kinetics of the organic ion exchanged resins was much slower and the total amount of ^{89}Sr removed after 1 hour was much less.

The exceedingly rapid kinetics can partly be explained by the fact that the nonatitanate was in the form of a fine powder, whereas the two resins were in the form of beads (see Table 1). As a consequence, a relatively slow reaction rate would be expected for the beads because the uptake of ^{82}Sr will be dependent upon the rate of diffusion of the ^{82}Sr to the internal functional groups. The rate of uptake of a sample of sodium nonatitanate pellets (using hydrous titanium dioxide as a binder) was significantly slower than the powdered form, but the kinetics and amount of ^{82}Sr absorbed was still significantly better than for either of the two organic resins. As the pelletization process is improved, it is expected that the kinetics and selectivity of the pelletized sodium nonatitanate will improve substantially. Other sodium nonatitanate powders of varying crystallinities also showed rapid kinetics. Other potentially suitable binders for forming suitable pellets include titanium isopropoxide or tetraethyl orthosilicate (TEOS) as a binder precursor.

Example 10 - ^{82}Sr Removal from Irradiated Targets Using Pelletized Sodium Nonatitanate

A sample of sodium nonatitanate was mixed with titanium isopropoxide as a binder and the resulting paste dried at 105°C for 12 hours. The material was gently broken up using a mortar and pestle and then sieved to produce particles in the range 40 to 60 mesh. The binder content was approximately 20%. These particles were then used to assess the extraction of ^{89}Sr from simulated target solutions.

1 mL of pelletized sodium nonatitanate was slurried into a column and the target simulant that had been spiked with ^{89}Sr to give an activity of approximately 200,000 cpm/mL was passed through the column at a flow rate of 15 mL per hour. The amount of activity removed from solution was then determined. The results are given below in Table 1.

Table 1. Removal of ^{82}Sr From Irradiated Target Solutions

Target	Solution Composition	Volume (mL)	^{82}Sr Removed (%)
Rubidium Metal	1.95M RbCl in 0.1M $\text{NH}_3/\text{NH}_4\text{Cl}$ Buffer, pH10	20	97.3
Rubidium Chloride	0.68M RbCl in 0.1M $\text{NH}_3/\text{NH}_4\text{Cl}$ Buffer, pH 10	20	98.8
Molybdenum Metal	0.26M Na_2MoO_4 , pH 12	20	99.9

This data clearly shows the effectiveness of sodium nonatitanate at removing strontium isotopes from ^{82}Sr target materials. Rubidium absorption under these conditions is minimal.

Example 11 - Elution of Strontium

Strontium was quantitatively eluted from the sodium nonatitanate column of Example 10 using 6M nitric acid. Hydrochloric acid was found to be much less effective and also resulted in breakdown of the sodium nonatitanate particles and blocked the ion exchange column.

While the foregoing is directed to the preferred embodiment of the present invention, other and further embodiments of the invention may be devised without departing from the basic scope thereof, and the scope thereof is determined by the claims that follow.